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MEAN QUADRATIC ANGLES OF INCLINATION OF THE SURFACES OF VENUS

N. N. Krupenio and K. M. Rykunova

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MEAN QUADRATIC ANGLES OF INCLINATION OF THE SURFACES OF VENUS

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ABSTRACT. The present study examines diagrams of the back-scatter of Venus measured in the course of radio location of that planet from the earth in the centimeter and decimeter ranges. Taking into account chemical composition and the temperature and pressure level profiles that were secured during the course of experiments on the interplanetary stations "Venus 4", "Venus 5", "Venus 6", and "Venus 7", a calculation of the weakening and refraction of radio waves in the atmosphere of the planet was carried out. This made it possible to draw diagrams of the back-scatter of the surface of Venus and to compute the mean quadratic angles of inclination of the surface, σ_α, on the basis of a series of 10 wavelengths in the range λ = 3.8:70 cm. As λ rises within this range, σ_α diminishes from 7.0 to 4.4°.

1. Introduction /3*

The flights of automatic interplanetary stations to Venus have made it possible to gain a better understanding of the sharp change, with length of wave, in the characteristics of the intrinsic radiothermal radiation and scattering of radio waves by that planet. It has been shown in a number of studies (for example [1-3]) that the sharp drop in radio-luminance temperatures, and also the reduction of the effective field of scatter of the planet at wavelengths shorter than 6 cm, are due to the influence of the dense atmosphere of Venus.

Measurements of the chemical composition, temperature, and pressure of the atmosphere performed by the Soviet automatic stations "Venus 4", "Venus 5", and "Venus 7" [4-7, 49], and also data on processing of radiophysical experiments carried out by the automatic station "Mariner 5" [8], have made it

*Numbers in the margin indicate pagination in the foreign text.

possible to create a more trustworthy model of the atmosphere of Venus [9]. This model, as calculations have shown, harmonizes well with the results of both radio-astronomical and radio ranging experiments [10, 11]. The possibility has arisen, through making use of this model and of data on the modeling and calculation of the characteristics of the propagation of radio waves in the gasses contained in the atmosphere of Venus, of arriving at a more reliable evaluation of the contribution made by the atmosphere of that planet to its radio wave radiation and in the formulation of the signal from the Earth re-emitted by Venus [10, 11]. Taking the influence of the atmosphere into account in this way enables one to evaluate certain characteristics of the surface and of the surface stratum of the planet, such as the dielectric penetrability of the surface stratum ε, the parameter of heat energy γ, and the mean quadratic angles of inclination of the surface σ_α.

We examine below only the last of these quantities and its dependence upon wavelength.

2. Results of Radio Measurements /4

The first attempts to apply radio measurement to Venus were made in 1958 and 1959. But these experiments were not successful because of the low energy potential of terrestrial radar. The first reliable measurements were carried out in proximity to the inferior conjunction of Venus in 1961 on wavelengths of 12.5; 43; 68 and 73 cm [17, 19, 22, 27]. Subsequently, radio experiments were continued in 1962, 1964, 1966 and 1967 [11-26, 41]. During the course of these measurements the following were determined: the effective field of scatter of the planet σ and its variations upon measurement of the longitude of the point being subjected to radar; the spectrum of the signal re-emitted; the diagram of back-scatter $B(\theta)$; the direction and period of rotation of the planet; and the distance from the Earth to Venus. These measurements were carried out on 11 wavelengths over the range 3.6 cm to 7.85 meters. In this process the effective field of scatter was determined on 10 wavelengths, and the diagram of back-scatter on 4 wavelengths.

The results of measurements of σ and $B(\theta)$ are shown in Table 1 and in Figures 1 and 2. As will be seen from Figures 1 and 2, as the wavelength becomes shorter a diminution of the magnitude of σ and an expansion of the diagram of back-scatter take place.

3. Attenuation and Refraction of Radio Waves in the Atmosphere

The presence of carbon dioxide, oxygen, and water vapor in the atmosphere of Venus brings about weakening of radio signals being propagated in its atmosphere as a result of the interaction of radio waves with molecules of the gasses in question. This weakening depends in essence upon the length of the wave, mounting as λ becomes shorter over the range of centimeter and millimeter waves. In studies [3, 11], on the assumption that the total decre- /5
ment of attenuation ae is the sum of the decrements of attenuation in CO_2, O_2, and H_2O, a calculation was made of the entire vertical attenuation η_n depending on wavelength at pressure values at the surface of the planet up to 50 atmosphere [3] for a preliminary model of the atmosphere constructed on the basis of data from the automatic station "Venus 4", "Venus 5", "Venus 6", and "Mariner 5" [8]. As the calculation showed, the weakening of radio waves in O_2 is, by reason of its low concentration in the atmosphere, considerably lower than in CO_2 and H_2O [11].

In calculating the attenuation of radio waves in a column of atmosphere not located above the point being subjected to radio location it is necessary to take into account the augmentation of the length of the path of the radio beam by reason of the increase in the thickness of the atmosphere and by reason of refraction. In these calculations it has been assumed that the atmosphere is concentrically stratified, in which connection in each stratum of thickness Δh_i the coefficient of refringence η_i and the vertical attenuation $\Delta\eta_i$ do not depend upon the planetocentric coordinates and the thickness of the stratum (when a sufficiently small thickness of this stratum is selected). The course of the radio beam and the designations adopted are shown in Figure 3. Here θ is the angle of incidence, a the radius of the planet, θ_0 the angle of entrance of the radio beam into the atmosphere, Δl_i the length of the course of the radio beam in the stratum Δh_i, ε' the angle of refraction, and ψ the angle of refringence.

In calculating the coefficient of refringence of radio waves in the atmosphere one may take into account only the effect of carbon dioxide, since CO_2 is the principal component of the atmosphere (CO_2:93 - 97%). The corrected coefficient of refringenge___ is determined according to the formula [31]:

$$N = (n - 1)\ 10^6 = K_5 \frac{P}{T}\ 10^6 \qquad (1)$$

where P is pressure at altitude H (atmospheres), /6

T is temperature at altitude H (degrees Kelvin),

K_5 is the coefficient (degrees Kelvin divided by atmospheres).

According to data from [31-35], the coefficient K_5 varies within limits 0.13 - - 14. In Figure 4 is shown the change curve N with altitude calculated according to (1) for the value K_5 = 0.13. The same diagram shows the dependence of T and P upon altitude, as constructed from data in [8]. Reckoning of the coefficient of refraction, the entire length of the course of the radio beam in the atmosphere L, and the entire coefficient of absorption of radio waves η for various angles of incidence was carried out by calculating these parameters for a stratum Δh located at an altitude H, and then integrating the results according to altitude. In these calculations the value for the radius of the planet, a, was taken to be 6,054 km, which is close to the maximum value determined from three radio measurements (a = 6,053, 2 ± 1, 3) [36, 37, 47, 48]. The calculation was carried out for a maximum altitude of atmosphere H = 100 km with Δh equalling 0.25; 0.05; 0.1; 0.2 and 0.5 km. As the calculations showed, changing the interval of integration from Δh = 0.025 km to Δh = 0.5 km (by 20 times) with $\theta = 76°$ led to increase the length of the course for an altitude H = 100 km by 0.2%, and with $\theta = 0°$ the increase in the length of the course came, at H = 100 km, to ΔL = 0.60 cm.

The formulas according to which the calculation was carried out are the following (see Figure 3):

$$n_i \cdot \sin\theta_i = n_{i+1} \cdot \sin\psi_{i+1} \tag{2}$$

$$n_i \sin\theta_i (a+H_i) = n_0 (a+H_0) \sin\theta_0 \tag{3}$$

$$\Delta\theta_i = \theta_i - \psi_i \tag{4}$$

$$\varepsilon' = \theta_0 + \sum_{i=1}^{m} \Delta\theta_i - \theta_m \tag{5}$$

$$\Delta l_i = \frac{(a+H_i)\sin\Delta\theta_i}{\sin\psi_i} \tag{6}$$

$$\Delta\eta_i = \Delta\eta_{in} \cdot \frac{\Delta l_i}{\Delta h_i} \tag{7}$$ /7

$$\eta = \sum_{i=1}^{m} \Delta\eta_i \tag{8}$$

$$\Delta\eta_{in} = \varkappa_{CO_2}(H_i) \cdot \Delta h_i + \varkappa_{H_2O}(H_i) \cdot \Delta h_i \tag{9}$$

The values for ae$_{CO_2}$ were calculated in accordance with [38], and those for ae$_{H_2O}$ in accordance with [39], taking into account the dependence of P and T upon altitude H [8] for lengths of waves from 8 mm to 15 cm. The results of the calculations are set forth in Figures 5, 6, and 7, where the dependences of the coefficient of refraction, the length of the course of the radio beam, and the entire attenuation of radio waves of the millimeter and centimeter ranges upon the angle of entry into the atmosphere (θ_0) are shown.

As one may see from the figures referred to, attenuation increases sharply with shortening of the wavelength and with increase of the angle of entry of the radio beam into the atmosphere, since with this increase the length of the course of the radio beam in the atmosphere rises. The increase in the length of the course comes to 20 with an angle of entry into the atmosphere $\theta_0 = 82°$. (hyper-refraction arises at $\theta_0 = 82°12'$ for P = 100 atmospheres).

4. Mean Quadratic Angles of Surface Inclination

Carrying out a combination of the diagrams of back-scatter of the planet $B_n(\theta)$ and of the dependence of entire attenuation upon the angle of entry of radio waves into the atmosphere, for the same lengths of waves, one can determine the diagram of back-scatter of the surface:

$$B(\theta) = B_n(\theta) - 2\eta(\theta) \tag{10}$$

In doing this one must bear in mind the fact that the diagrams of back-scatter of the planet are measured relative to the angle of entry of radio waves into the atmosphere, θ_0, and the diagrams of back-scatter of the surface of the planet must be related to the angle of incidence, θ, which is equal to:

$$\theta = \theta_0 - \Delta\theta, \tag{11}$$

where $\Delta\theta \approx \varepsilon'$ and is calculated according to formulas (1-5). /8

Such calculations were carried out for wavelengths λ = 3.8 and 12.5 meters, and for these wavelenghts diagrams of back-scatter of the surface were secured (see Figure 8). At longer wavelengths (λ = 23 and 70 cm) the effect of the atmosphere upon the propagation of radio waves is insignificant, and for that reason the diagrams of back-scatter of the surface at these lengths of wave are identical with the diagrams of back-scatter of the planet (refraction being taken into account). The diagram of back-scatter of the surface furnishes information regarding the proportions of its heterogeneities, both large-scale and small-scale (relative to the length of the wave of the irradiating flow). The large-scale heterogeneities are the cause of the quasi-specular component of the transradiated signal, and the small-scale ones produce the diffusely scattered signal.

The method for separating the signal transradiated by the complicated surface into diffusion and the quasi-specular component has been discussed in a number of studies [40-43], in which it has been shown that the result of the separation depends upon the rule selected for distribution of unevennesses along the surface, and upon the rule for distribution of heights of unevennesses relative to the mean surface of the planet. We made the assumption that the diffusion component of the transradiated signal is subject to Lambert's law, which has for a spherical surface the form:

$$B(\theta) = \cos^2(\theta), \tag{12}$$

and that the quasi-specular component is conditioned by reflection from flat laminae, disposed at random relative to the mean surface, and having dimensions exceeding the length of the wave, distribution of the inclinations of these being subject to Gauss's law:

$$P(\alpha) \approx \exp\left[-\frac{\alpha^2}{2\sigma_\alpha^2}\right] \tag{13}$$

where σ_α is the mean quadratic angle of inclination of the large-scale unevennesses. /9

According to Hagfors [44] the quasi-specular component of the diagram of back-scatter of a surface may be represented in the form:

$$B_3(\theta) = \left(\cos^4\theta + C_3\sin^2\theta\right)^{-3/2} \tag{14}$$

where

$$C_3 = \left(\frac{l\lambda}{4\pi H_n^2}\right)^2$$

l is the radius of correlation of the large-scale heterogeneities, and H_n is the mean quadratic height of the large-scale heterogeneities. The parameter C_3 is directly linked with the value of the mean quadratic angle of inclination [29]:

$$\sigma_\alpha \approx C_3^{-1/2} \cdot \cos\theta \tag{15}$$

For this reason, once one has determined from the experimental diagram of the back-scatter of the planet $B_n(\theta)$ the diagram of the back-scatter of the surface of the planet $B(\theta)$, and once one has isolated from it the quasi-specular component $B_3(\theta)$, one can select an approximating curve subject to rule (14) with an appropriate value for C_3. One may thereafter determine in accordance with formula (15) the value of the mean quadratic angle of inclination of the surface.

Such calculations were carried out for all measured diagrams of the back-scatter of Venus for lengths of waves λ = 3.8; 12.5; 23, 43 and 70 cm. The results of the calculations are presented in Figures 9, 10, where the dependences of the parameters C, C_3, and σ_α upon wavelength are shown.

The quantity C, shown in Figure 9, is a parameter forming part of the Hagfors formula for the approximation of the diagram of the back-scatter of the planet relative to the angle of incidence of a beam on the surface:

$$B_n(\theta) = (\cos^4\theta + C\sin^2\theta)^{-3/2} \tag{16}$$ /10

In Figures 9 and 10 we show by means of a dash-line and unblackened symbols the results of the calculation of the parameters C, C_3 and σ_α for the case of the absence of attenuation of radio waves in the atmosphere of Venus.

5. Evaluation of Results

A comparison of the frequency course of the dependence of mean quadratic angles of inclination of the surface of Venus for a model without atmosphere, and for an atmosphere having a pressure at the surface around 100 atm, shows that:

1. The observed diagrams of back-scatter of the planet may be interpreted through non-dependence of the mean quadratic angles of inclination of the surface upon wavelength if one does not take into account the effect of the atmosphere (absorption and refraction). If this is done, the value of the mean quadratic angle of inclination of the surface comes to about 5°, which is somewhat greater than for the surface of Mars (about 3°) [45] and less than for the surface of the moon [43] with measurements being made on the same wavelengths.

2. Taking into account the effect of the atmosphere points toward an increase in the value of the mean quadratic angle of inclination of the surface of Venus as the wavelength becomes shorter. When λ changes from 68 cm to 3.8 cm, σ_α increases from 4.4 to 7.0°. According to study [28], the methods system

for determination of σ_α which is at issue applies to bases of wavelength order 10, which corresponds to a value from 40 cm to 10 m on the surface of the planet.

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TABLE 1. /15

Wavelength, λ, cm	Effective area of scatter as related to area of disc, $\sigma/\pi a^2$	Precision of measurement, gδ	Year of measurement	Source
3,6	0,0I	± 2	I964	I2
3,8	0,0I7	± 2	I967	I4
3,9	0,0I7	±2	I966	I3
I2,5	0,II4	± 0,5	I964	I5,I6
23	0,I5	± I	I964	I8
43	0,I57	± 2	I962	2I
43	0,I9	± 2		20
68	0,I3	± 2	I96I	22
70	0,I4	± 2 3	I964	24
600	0,2	± 2	I962	25
784	0,I5	± 2	I962	26

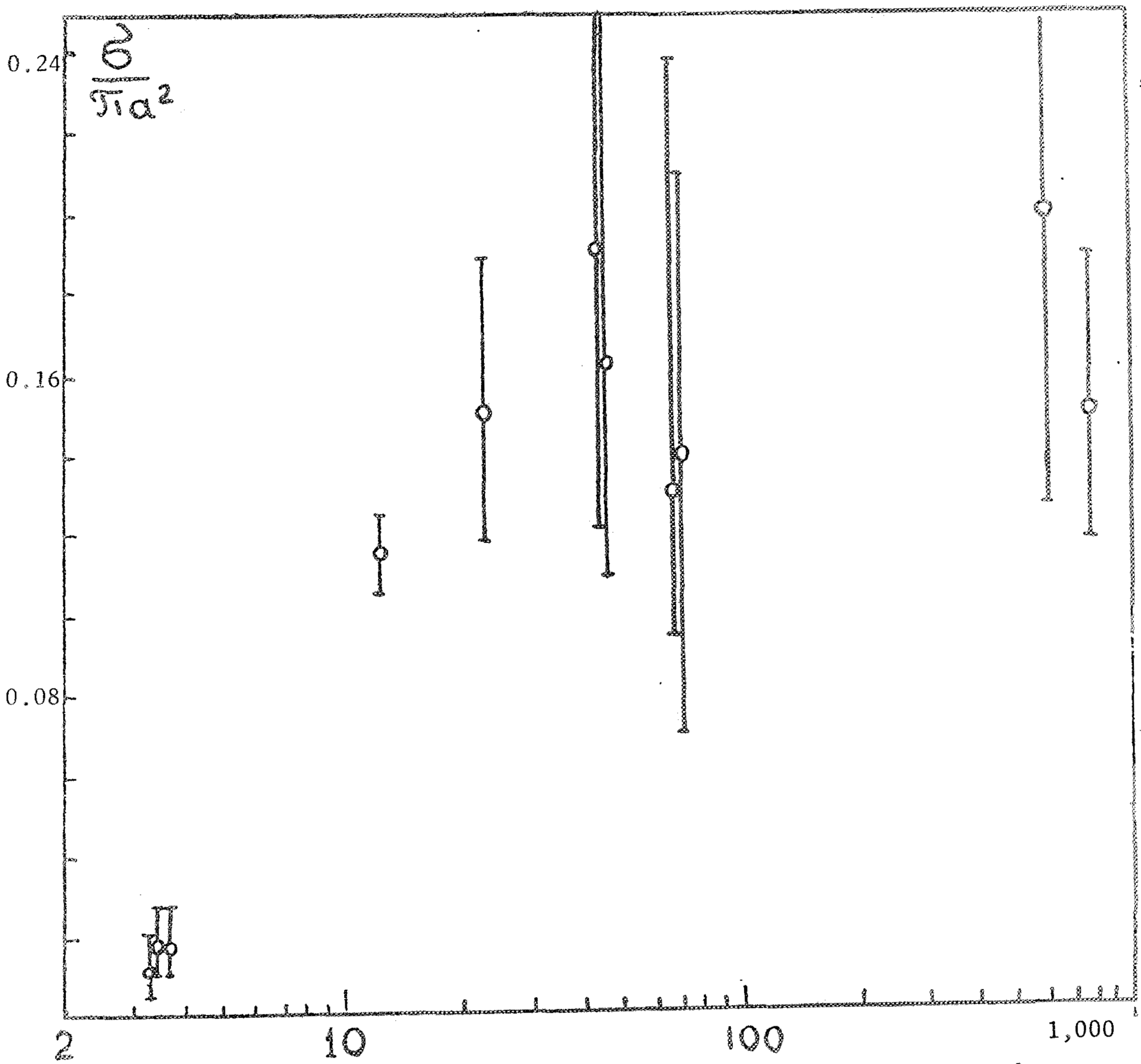

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Figure 1. Effective Area of Scatter of Venus in Centimeter, Decimeter, and Meter Ranges.

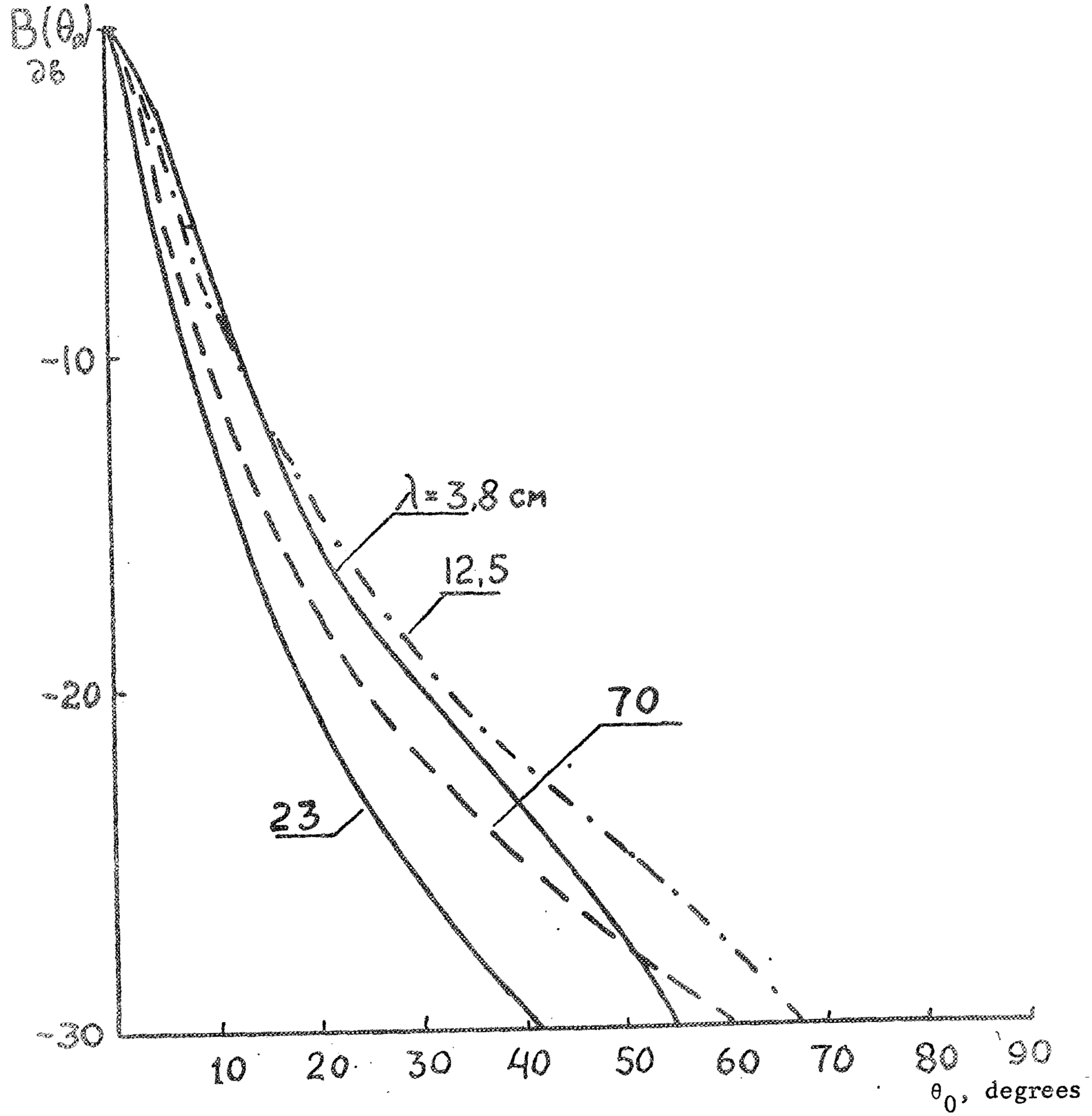

Figure 2. Diagrams of Back-Scatter of Venus (atmosphere taken into account).

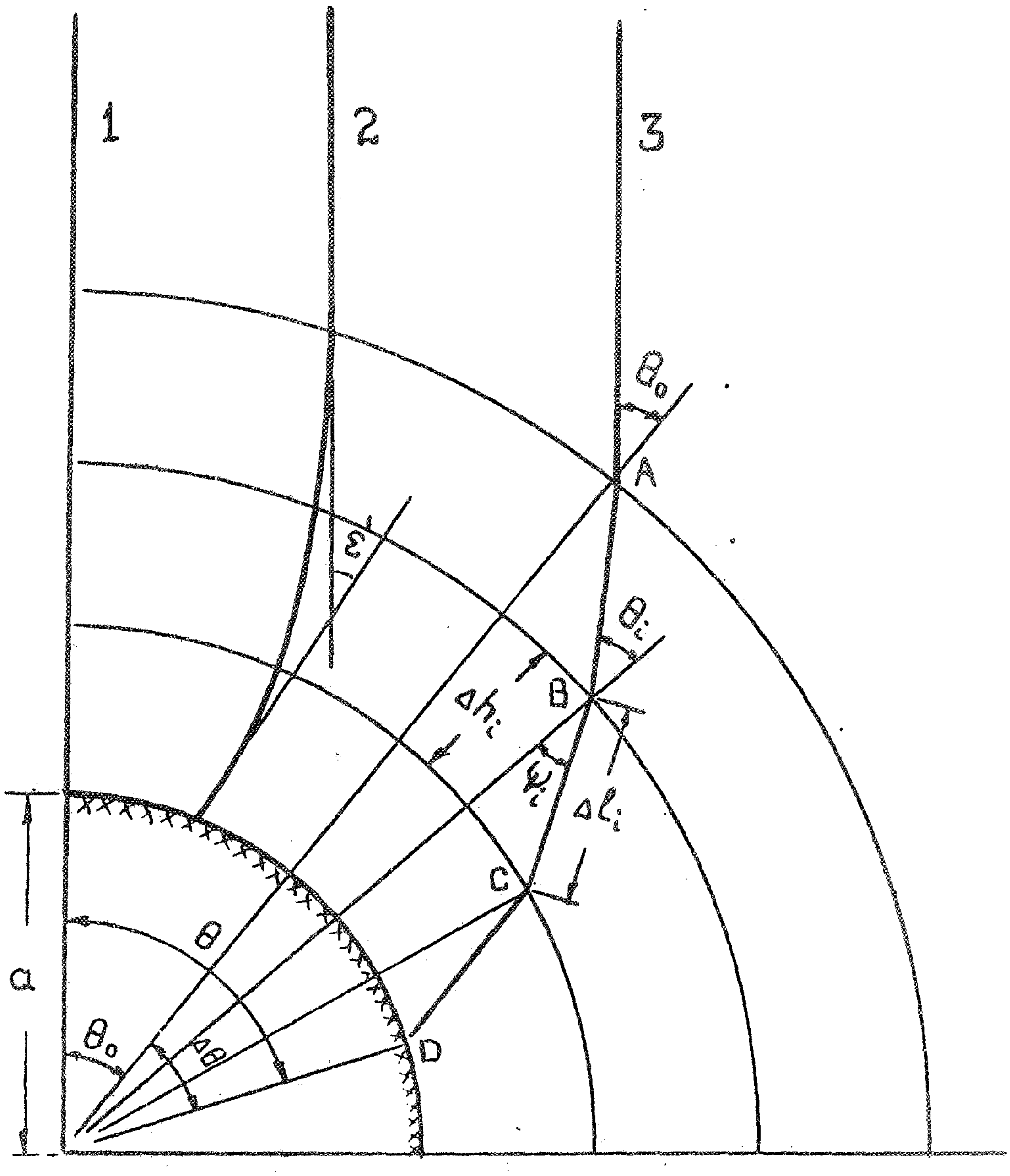

Figure 3. Course of Radio Beam in Atomsphere.

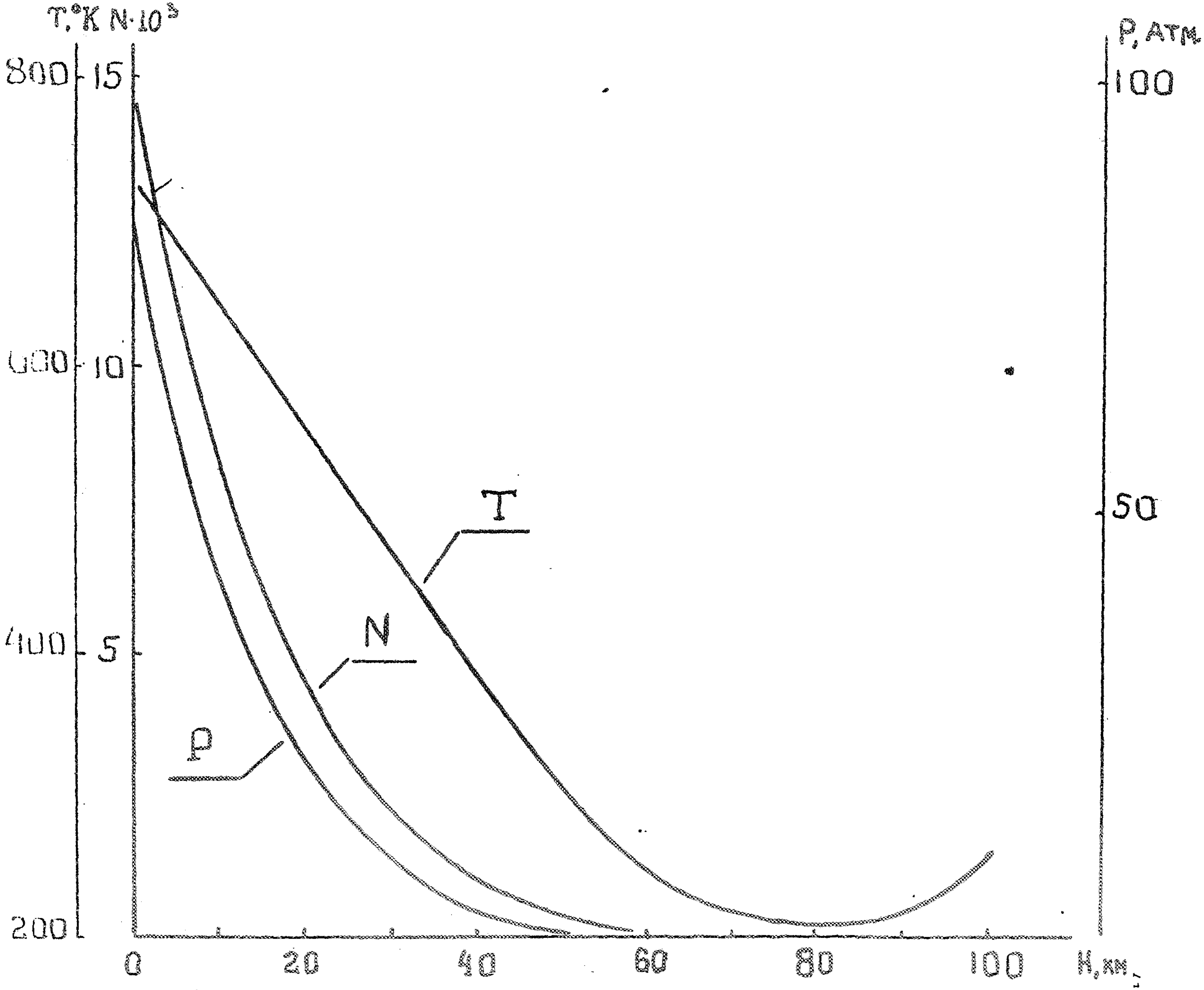

Figure 4. Coefficient of Refringence N, Pressure P, and Temperature T, T, Depending on Altitude Above Mean Surface of Venus (With a ≈ 6054 km).

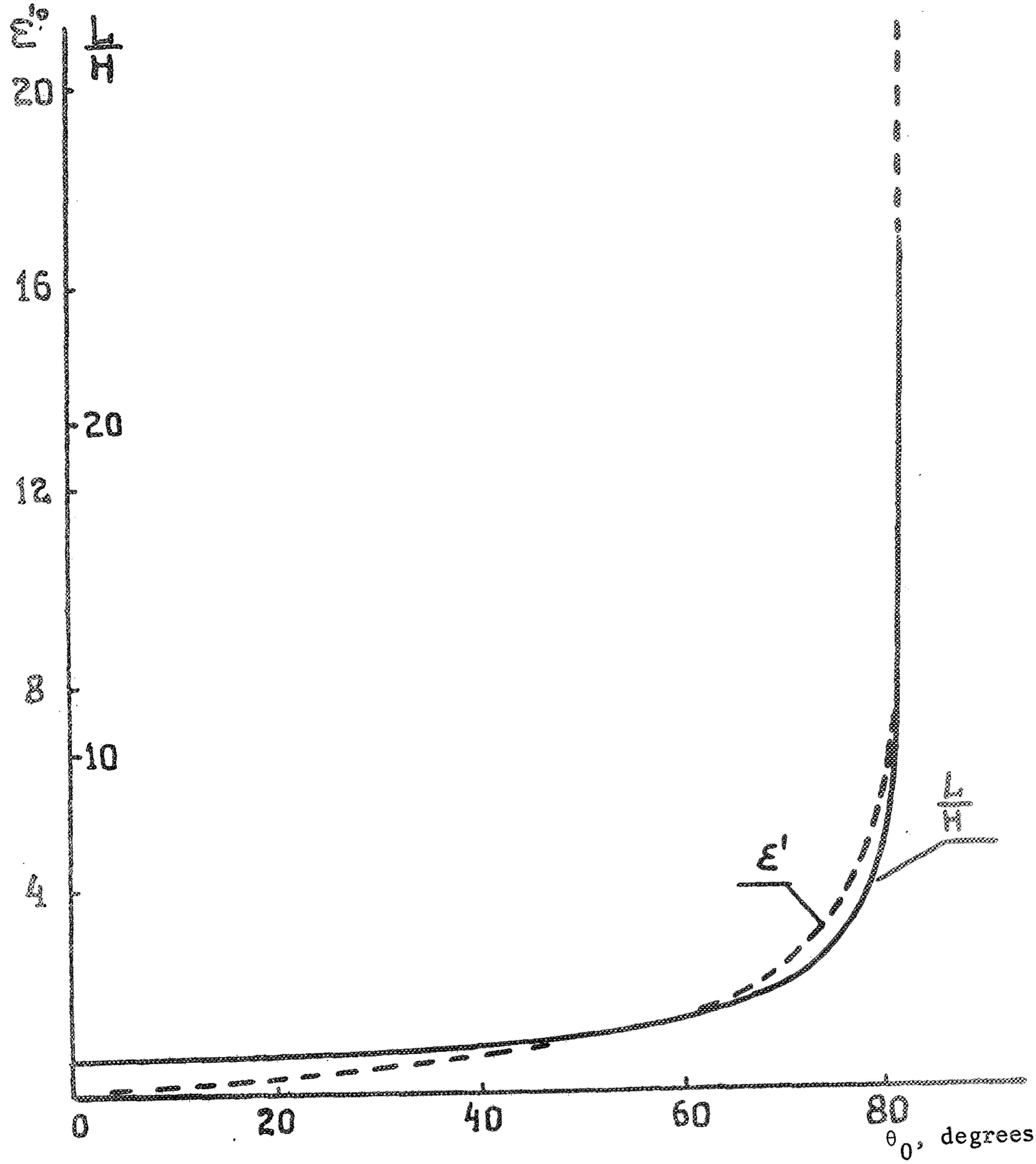

Figure 5. Dependence of Coefficient of Refraction ε', and of Relative Length of Course of Radio Beam L/H, upon Angle of Entry of Radio Beam into Atmosphere of Venus, θ_0.

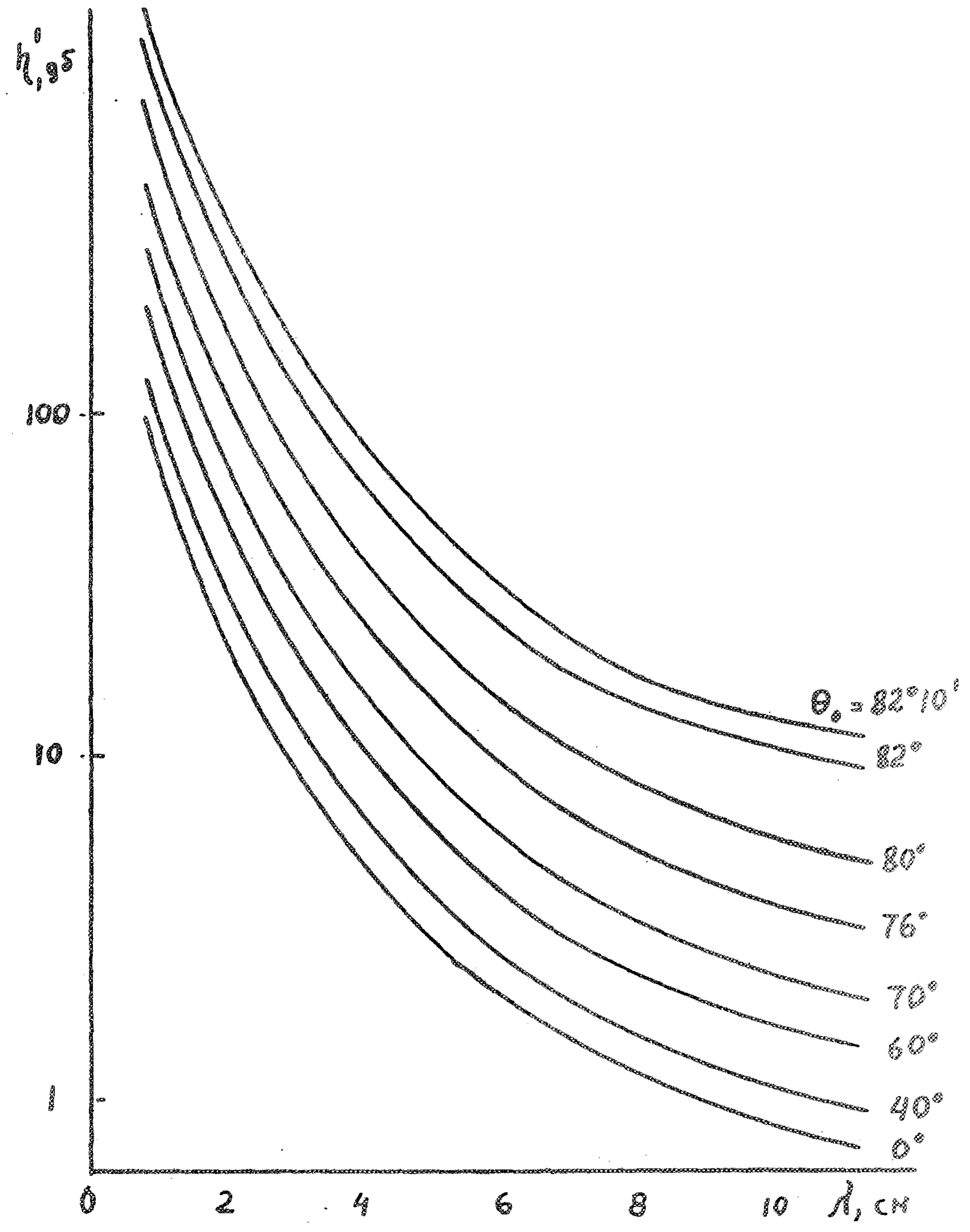

Figure 6. Dependence of Entire Attenuation of Radio Waves of the Millimeter and Centimeter Ranges upon the Angle of Entry of Radio Waves into the Atmosphere.

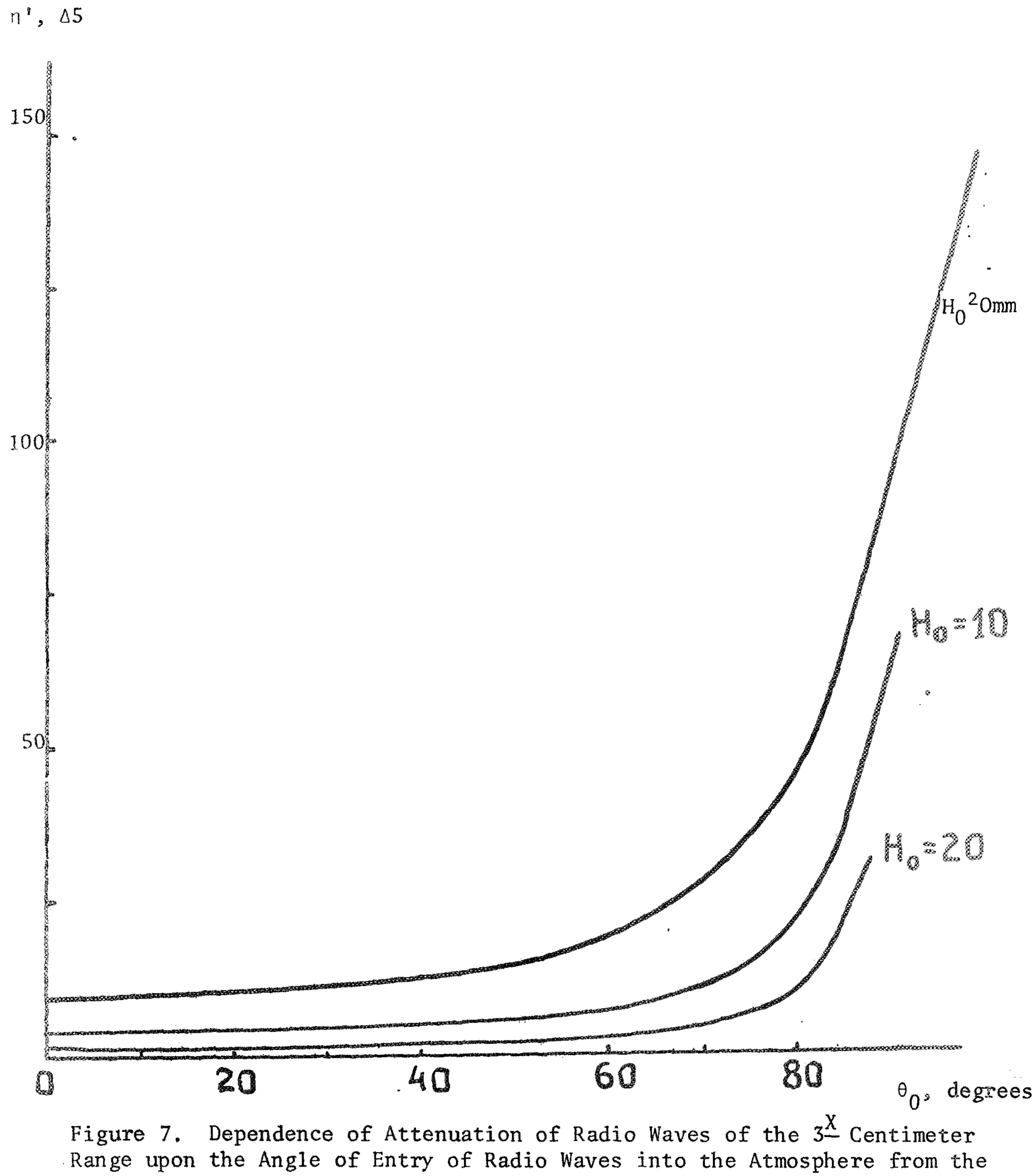

Figure 7. Dependence of Attenuation of Radio Waves of the $3^{\underline{X}}$ Centimeter Range upon the Angle of Entry of Radio Waves into the Atmosphere from the Upper Limit of the Atmosphere (H_{max} = 100 km) to Altitudes above the Surface H = 0.10 and 20 km.

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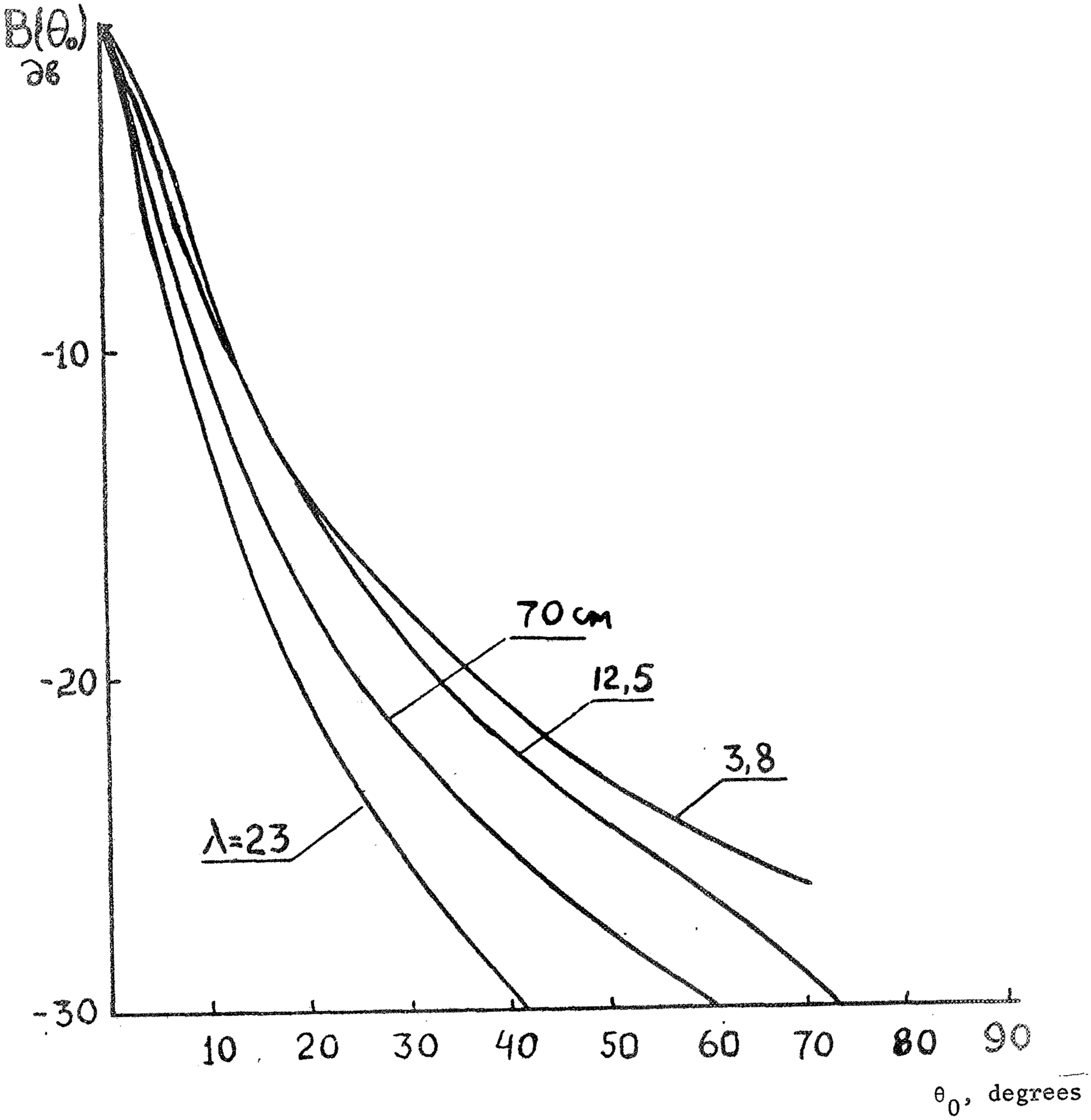

Figure 8. Diagrams of Back-Scatter of Surface of Venus.

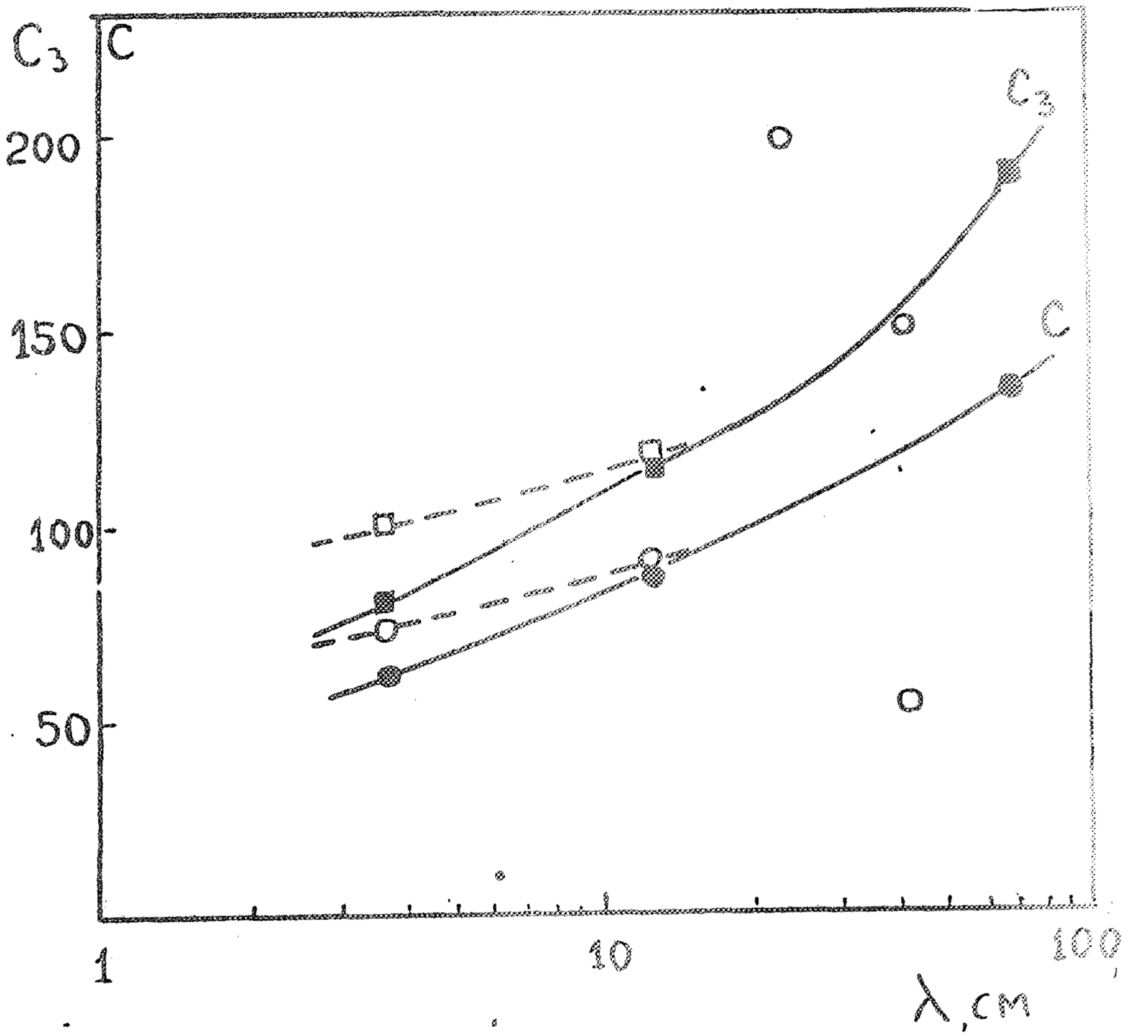

Figure 9. Dependence of Parameters C_3 and C upon Wavelength for Surface of Venus.

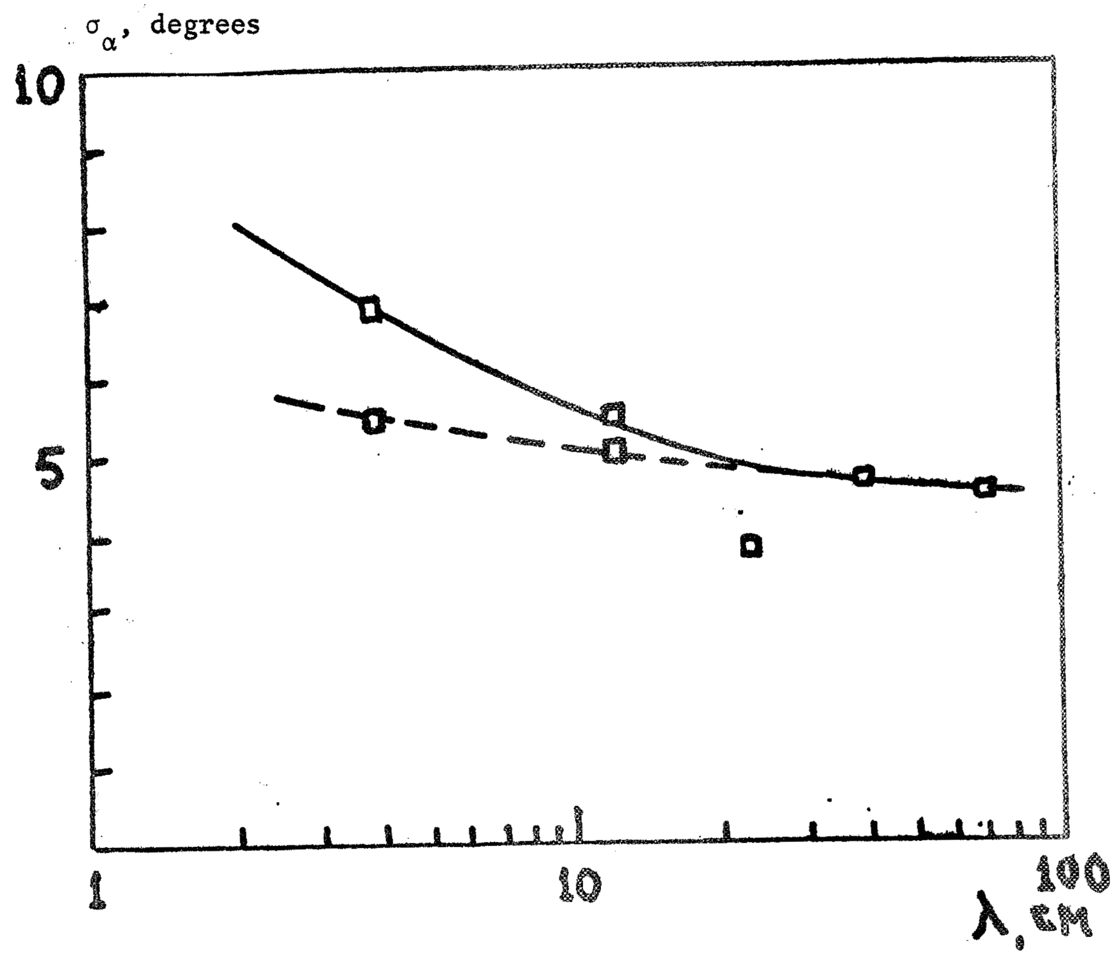

Figure 10. Mean Quadratic Angles of Inclination of Surface of Venus.

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